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INJECTION LASER MODE STUDIES

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JUNE 1980

FINAL REPORT
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Contract No. DAAG29-77-C-0021
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This document is the sixth semiannual report and the final report of a basic study of the modes of injection lasers. The concern is the fundamental relationship between the modal properties of diode lasers, their structure, and the nature of the electrical drive.

The semiannual report features three pioneering studies: The development of an equation of state relating the laser power, spectrum,

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and beam profile to the input current and laser structure; the behavior of the laser on transition of threshold as the current is increased through the immediate vicinity of threshold; and the comparison of the laser spectrum under pulsed drive to excitation with a dc current. It also touches on the behavior of quarternary lasers operating at 1.2 μm.

The final report describes five studies which produced the most important results under the contract: (1). An experimental and theoretical study of the current distribution in oxide-stripe lasers. (2). The comparison of the modal properties of lasers with an optical waveguide produced by the fabrication to the properties of lasers in which the excitation itself produces or modifies the guide. (3). An original proposal for the measurement of the internal efficiency and loss coefficient on individual lasers, parameters which were previously available only by a laborious statistical study of a collection of related units. (4). The equation of state of injection lasers described in the sixth semiannual report. (5). The dependence of injected carrier density on modal power from the region of drive producing an LED to the full coherent output.

The report concludes with a consideration of the outstanding fundamental problem at the present time, the dynamic interaction of the laser which reduces the number of spectral lines in the coherent output of a laser as the current drive is increased.

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I. STATEMENT OF THE PROBLEM AND THE COURSE OF STUDY

This three-year contract supported a fundamental study of the relationship between the modal properties of injection lasers and their structural and material properties, with particular emphasis on the behavior of narrow-stripe lasers being developed for optical communication via fibers. The guide to the open-ended program was the nonlinear P* theory of lasers [1] which was developed in the RCA Laboratories and was found to give a useful description of the behavior of high-power pulsed lasers. This multimode theory provides a much needed analytical connection between the modal excitations and the gain and loss coefficients of each lasing mode. The underlying rationale was the expectation that experimental study of these parameters on representative lasers would lead to useful predictive relations of the material and structural properties of the device to the power dependence of the radiated beam and spectrum.

Initially, the problem of most practical concern was the control of the beam profile, and the first work concentrated on the cavity modes in the plane of the p-n junction. With the development of internal structures which confined the radiation to a single off-axis mode, the interest shifted to another aspect, the tendency of the power spectrum of such lasers to become simpler (fewer spectral lines) as the power increased, and the occurrence of regions of drive in which the output was dominated by a single mode. During the last year we concentrated on the study of this "single-mode" behavior. Finally, the improvement of optical fibers has shifted the development interest to lasers in the range of 1.2 to 1.6 μm, and a study of such units was initiated.

1. H. S. Sommers, Jr., and D. O. North, Solid-State Electron. 19, 675-699 (1976).

II. PROGRESS IN THE FINAL PERIOD OF THE CONTRACT

The last half-year of the contract extended the examination of single-mode lasers to include the Hitachi buried optical guide (BOG) laser with the cavity formed by four heterojunctions, and to quarternary lasers operating around 1.2 μm.

A. AlGaAs SINGLE-MODE LASERS

The work concentrated on the Hitachi BOG laser for comparison with the earlier results on the Mitsubishi transverse junction stripe (TJS) laser, on the oxide-stripe lasers, and on RCA's confined double-heterojunction (CDH) laser. This covers the most important commercial types except for the Bell Telephone Laboratories' proton-bombarded-stripe laser which was not available to us. Earlier studies of proton-bombarded units made in-house showed no fundamental difference in their modal power sharing.

1. P(V) Above Threshold

With pulsed drive, the power in individual modes was linear in junction voltage for mode powers exceeding a fraction of a mW. Except for the two Hitachi units, all values of the nonlinearity constant P* defined by the measured value of dP/dV lay in the range 10 to 20 mW. The value for the Hitachi units was between 40 and 50 mW. It is not known whether the difference is real, or whether it originates in uncertainties about the algorithm for deducing P* from dP/dV. The algorithm contains a number of geometric and material parameters of the device which vary considerably with laser structure and are not known precisely.

2. Evidence for Spatial Hole Burning

None of these units gives evidence of spatial hole burning. Of particular note, the study included a CDH laser which emitted nearly 90 mW in one mode (power density near 4 MW/cm^2). This intensity is some three orders of magnitude above the threshold value and at least an order of magnitude greater than the normal range of stripe lasers.

3. Threshold Region

An extensive pioneering study of the transit of threshold has given the first experimental description of the passage from the LED state to the oscillator. It is a stringent test of any theory of laser action. The observed behavior is inconsistent with the popular description of lasers based on the linear approximation to the rate equation plus a perturbation based on either spatial or spectral hole burning.

The study is the measurement of the power in each major mode as a function of the junction voltage over the range from well below threshold to full output. A typical result is shown in Fig. 1, the behavior of a commercial Hitachi BOG laser excited by 20-ns current pulses. With such a short pulse, the same axial mode (the circles in the figure) dominates the lasing spectrum. The crosses describe the behavior below threshold, where a number of modes have nearly equal powers. The horizontal scale is the overdrive parameter $X = (g/g_{th}) - 1$, which has been deduced from the measured changes in the junction voltage by recourse to the band calculations of Stern [2] for GaAs. These show that the gain is linear in voltage for small changes in g/g_{th}; hence, X is also linear in voltage for lasers in which the threshold gain is independent of drive, i.e., for passive waveguides.

The solid curve in Fig. 1 is the steady-state solution of the P* theory for the dependence on gain of the mode power. The dimensionless solution is

$$y(X) = \frac{X + Z}{2} + \left| \left[\left(\frac{X + Z}{2}\right)\right] + Z \quad ^{1/2} \right| . \qquad (1)$$

The overdrive parameter, X, is linear in mode gain, y(X) is the normalized mode power, and Z is a dimensionless surrogate for the spontaneous emission. It can be treated as a constant over the range of study and evaluated from the measured y(X) in the subthreshold range ($X < 0$).

For all negative X except the immediate vicinity of zero, Eq. (1) describes also the behavior of the linear model of lasing, which is

$y = Z/|X|$, or

$$P = \text{spontaneous factor}/(g_{th} - g). \qquad (2)$$

The dashed curve in Fig. 1 illustrates the divergence of the linear approximation as g approaches the threshold value g_{th} (as X grows to zero). The dot-dash

2. F. Stern, J. Appl. Phys. 47, 5382 (1976).

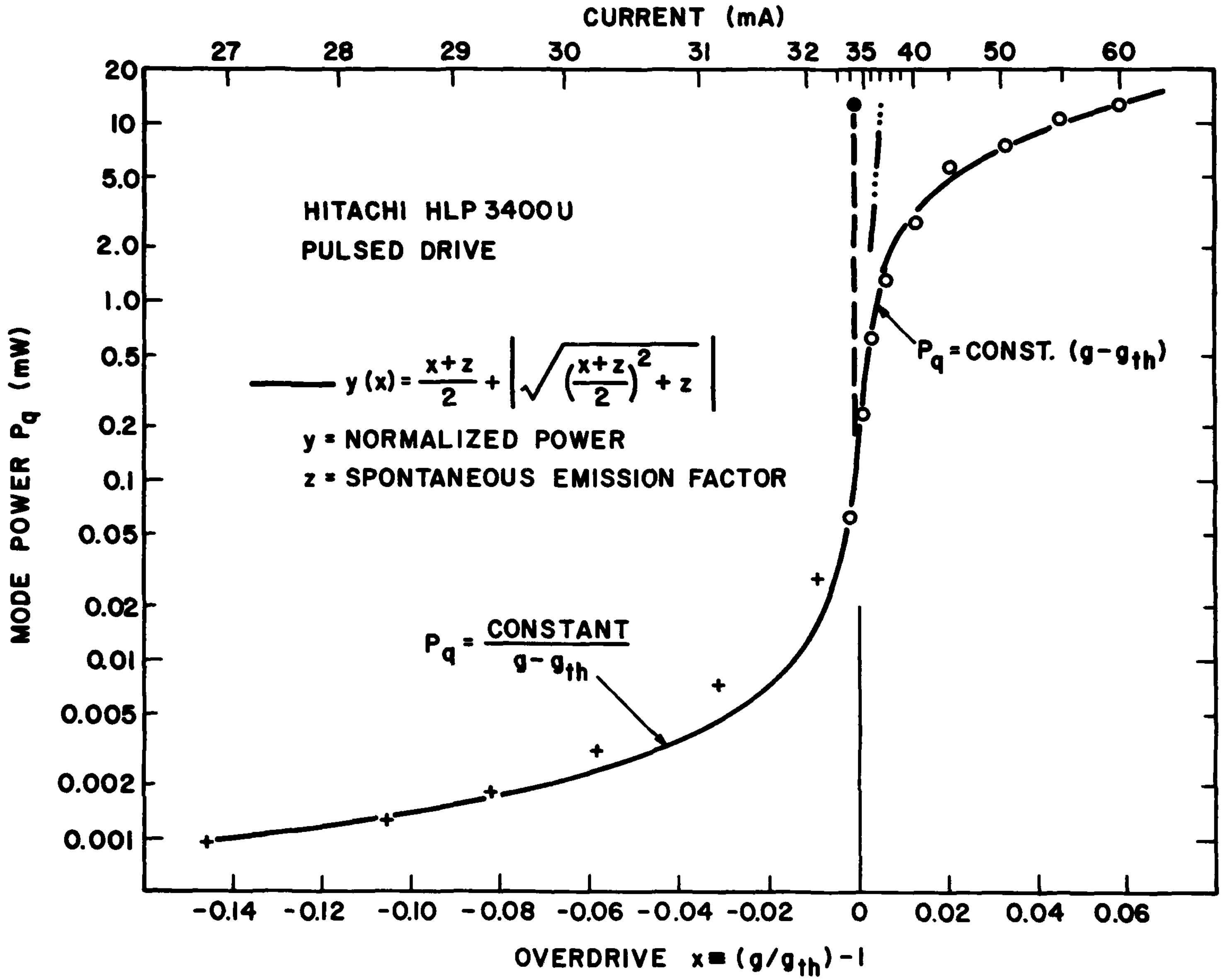

Figure 1. Dependence of the power in the strongest mode on mode gain. Hitachi BOG "Single-Mode" Laser.

line illustrates the typical result on addition of a perturbation to the linear theory to improve the description of the lasing region. The line drawn corresponds to the recent theory of Yamada and Suematsu [3] of single-mode lasers. Their perturbation is intended to describe a distortion of the carrier distribution produced by spectral hole burning. The conclusion from the study as represented by Fig. 1 is that the gain distortion from their perturbation is negligible compared to the total change in gain with lasing power, and that such a perturbation is inconsequential. The same conclusion applies to perturbational treatment of spatial hole burning.

For $X > 0$, Eq. (1) takes on the simple form of mode power linear in gain

$$P = bP^{*}X, \tag{3}$$

and the experimental behavior in this region determines bP^{*}. A theoretical algorithm relates b to geometric properties of the device and permits experimental evaluation of P^{*}.

Another interesting new feature of Fig. 1 is the actual value of mode power at threshold: At $X = 0$, $P_q \approx 0.1$ mW.

4. Comparison of Spectrum with Pulsed Current and dc Excitation

We found a considerable difference between the axial mode spectrum for a laser driven with pulses compared to those with dc drive. It is not known how many of the effects are due to change of the internal temperature or temperature profile, and how many are associated with a more involved modification of the material.

a. Mode Hopping - Mode hopping (the abrupt transfer with incremental current changes of the power from one mode to an adjacent mode) is a well-known feature of single-mode lasers. We do not find it with short current pulses (20 ns), for then the mode powers change smoothly with current and the same mode is dominant at all currents. The effect has long been associated with the temperature shift of the wavelength of the peak of the gain spectrum relative to the wavelength of a cavity mode.

We observed, in addition to the mode hopping with change in current, an oscillatory hopping at fixed current. On occasion, we observed a 100% square-wave modulation of the power in the strongest modes which appeared when adjacent

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3. M. Yamada and Y. Suematsu, Jpn. J. Appl. Phys. 18, 347-354 (1979).

modes had comparable powers. As noted by others in a study of laser noise [4], the fluctuations of individual spectral lines were not reflected in the total output, which is consistent with our observation of mode hopping at fixed current and power. Observed hopping frequencies ranged from kHz to MHz. At least some of the instability was related to reflection from the optics used to monitor the output, and in particular, from the surface of the entrance slit of the spectrometer, which acted like the end mirror of an external cavity.

b. Power Dependence of Spontaneous Emission - We often observed a difference in the current or power dependence of the intensity of short wavelength emission as the drive changed from short pulses to long pulses and to dc. This indicated a steady decrease in the current-dependence of junction voltage (in the dynamic resistance of the junction) with an increase of pulse length. In most lasers the effect was too small to require inclusion in our analysis of the gain dependence of mode power. In the two Hitachi units, however, the dynamic resistance dropped to nearly zero with dc excitation, and in some anomalous units from our own wafers it even changed sign.

We do not know the cause of the change of junction resistance with pulse length nor its implication about the lasing state. If it is a simple temperature effect described by band theory, the drop of junction resistance to zero would imply a profound change in the relation between mode power and overdrive X, i.e., in the fundamental interaction between the circulating power and the inverted population. If, however, the effect is more complicated and results from changes in mode gain or loss at fixed inversion, then the observed behavior would merely imply a change in the relation between junction voltage and X. For example, our algorithm for X(V) assumes a rigid waveguide with fixed modal loss coefficients. It could be quite different if the waveguide was seriously modified by the drive, as in some oxide-stripe lasers, or if the circulating power changed the occupancy of localized states, as has been postulated to explain Q switching and some types of gradual degradation.

This difference of the effect of pulse length on dynamic resistance between the two BOG lasers and the other units needs further study. There is even the possibility that the effect is connected to the single-mode behavior itself, which often shows a dependence on pulse length.

4. T. Ito, S. Machida, K. Nawata, and T. Ikegama, IEEE J. Quantum Electronics QE-14, 574 (1977).

B. InGaAsP QUARTERNARY LASERS

The study of mode powering was extended to quarternary lasers. Because of the longer wavelength of the alloy, the measurements are more difficult and only preliminary results have been obtained. Technical problems arise from the lower detector sensitivities, since photomultipliers are not available, and the short supply of suitable bandpass filters for the study of the short-wave spontaneous emission to deduce the junction voltage.

The dependence of mode power on junction voltage is similar to that for the alloy AlGaAs, indicating that the nonlinearity which stabilizes the amplitude of the oscillation is similar in the two systems. No value of P^* has been deduced as yet, but it appears to be of the same order of magnitude as for the ternary alloy.

III. THE MOST IMPORTANT RESULTS OF THE WORK UNDER THE CONTRACT

The Appendix contains the abstracts of the papers published under this contract, which is the written record of the study. The following section summarizes the noteworthy contributions of the three-year program, all of which were pioneering observations. The references in the headings are to the corresponding appendices.

A. SPATIAL DISTRIBUTION OF CURRENT IN OXIDE-STRIPE LASERS. (Appendix A)

The current distribution in a planar laser with a stripe contact was previously calculated by Dumke [5], who modeled the laser by a homogeneous p-layer between the metallic stripe contact and the homogeneous n-layer; and by Hakki [6], who assumed the current density at the p-n contact was uniform and that the distribution was determined by lateral diffusion in the recombination region. Both assumed uniform current density beneath the contact, a poor approximation. No reported study has compared the measured spatial distribution to the theoretical prediction.

To better understand the properties of oxide-stripe lasers, we conducted an extensive experimental study of the actual current distribution in the recombination region. Since neither theoretical model applied to our lasers, (contrary to Hakki's model, diffusion is unimportant, while our structure has a conducting cap between the metal stripe and the p-layer which vitiates Dumke's analysis), we developed a model which applies to our units. It is a two-layer model, with <u>two</u> planar layers between contact and recombination region, and gives a rigorous analysis of the current distribution under the contact which turns out to be far from uniform. The model gave a most satisfactory description of the observed current distribution, both below and above threshold, and a simple way to visualize the behavior. To good approximation the device can be considered to be a <u>passive</u> structure with current pattern determined by the contact and the two resistive layers. The effects of the p-n junction and the onset of lasing are only minor.

5. W. P. Dumke, Solid-State Electron. 16, 1279 (1973).
6. B. W. Hakki, J. Appl. Phys. 44, 5021 (1973).

B. COMPARISON OF MODAL PROPERTIES OF LASERS WITH RIGID WALLS TO THOSE WITH WALLS MODIFIED BY THE OPERATING CONDITIONS. (Appendices G, H.)

It was long known that the waveguide of oxide-stripe lasers was modified by the operating conditions, but the cause of the modification was never experimentally demonstrated. Of the suggested sources of modification, those considered most important were changes with pumping of the gain profile and of the free carrier profile.

Comparison of the behavior of CDH lasers, whose optical waveguides are produced by the processing rather than the operation, to oxide-stripe lasers gave several important results. At the onset of the current pulse, both types were similar in that their mode powering followed the P* theory for a cavity with rigid walls. With delay after the pulse onset, the properties of the oxide-stripe laser changed drastically, displaying a considerable modification of the beam profile of the fundamental mode and wild changes in the power spectrum; in contrast, the minor modification with delay of the CDH laser was only that associated with a shift with temperature of the gain spectrum. The conclusions were that the growth of the temperature profile was the most important perturbation to the dielectric waveguide of the oxide-stripe laser; that gain guiding was a relatively minor contribution to the waveguide; and that undesirable properties such as kinks in P(I) and shifts in the spectrum were probably due to waveguide changes in the presence of inhomogeneities in the material.

C. METHOD TO MEASURE INTERNAL EFFICIENCY AND LOSS ON INDIVIDUAL LASERS. (Appendix B)

Interpretation of laser properties in fundamental terms has always been hampered by lack of a satisfactory method of measuring the internal efficiency and loss of individual lasers. The only available method requires study of a statistically significant sample of lasers of assorted lengths cut from one wafer, measurement of their thresholds and external efficiencies, and fitting the theory to the average behavior. Parameters of single units were available only by inference. Moreover, uncontrollable variations among experimental units from any particular wafer so restrict the applicability of the method that few such studies have been reported.

The new technique poses an analytical method of extrapolating the normal diode equation for the voltage dependence of the forward current in the sub-threshold region to cover the lasing region. The formalism reveals a direct way to determine the fraction of the total current that drives the lasing modes by study of only the current dependence of the short wavelength spontaneous emission. The internal efficiency results from measurement of the relative spontaneous intensity at short wavelength without recourse to measurement of an absolute power. The internal loss requires the additional measurement of the absolute external efficiency. The method is simple and seems to be reliable. It even gives useful information about abnormal units such as lasers with non-linearities or kinks in P(I).

D. EQUATION OF STATE OF INJECTION LASERS. (Appendix I.)

System engineers require detailed information about the output of the device in terms of the controllable input. Preferably, this information has the form of an analytic equation of state of the device. For injection lasers, it should give the dependence on input current of the beam profile, spectrum, and transient response.

The many published attempts to develop such a formalism have met with little success. All have been based on the description of the lasing state by linear perturbation theory; to deduce any quantitative results, they have restricted the analysis to a model laser oscillating in only one mode. The region where perturbation theory is best applied, the immediate vicinity of threshold, is the one where no such laser has been reported; around threshold, actual lasers have been multimode.

The new insight that led to the study of the internal efficiency also revealed a way to develop a comprehensive description of real lasers. The formalism involves a combination of the model for the partitioning of the current between the component driving the lasing modes and the remainder (see preceding section), the expressions of North [1] for the dependence on gain of the steady-state power in each mode, and the dependence of gain on bias voltage from the band theory of Stern. The combination gives the first analytic description of the current dependence of the steady-state power in every mode of the laser.

The new formalism goes to the heart of laser study. It details the device parameters which must be known and controlled to apply the equation of state to particular classes of devices, and it reveals new connections between the parameters and various geometric scaling laws. A full test of the generality and utility of the new insight requires accumulation of experimental and theoretical information about certain parameters of the laser which are neglected in the perturbation theory. Because of the general acceptance of the perturbation model, it has not been customary to report the experimental values of these device properties. An extensive test of the equations awaits further experimental knowledge of the parameters and more detailed modeling of the optical waveguide.

E. VOLTAGE DEPENDENCE OF MODAL POWER FROM WEAK STIMULATION TO FULL LASING. (Appendix J.)

A continuing experimental study of the threshold region has yielded a complete curve of the dependence on gain of the modal power from the LED state through threshold into full lasing. To the best of our knowledge, no such study has been reported for any laser whatsoever. The only previous description of the vicinity of threshold which we know of, is a single study on an He-Ne laser [7].

This work is described in the accompanying semiannual report for the final period of the contract. The outstanding conclusions from the work are that perturbation theory does not apply to the range of gain where single-mode lasing is observed, and that the nonlinear P* theory gives an adequate account of the entire power range from a fraction of a microwatt to many milliwatts of mode power. However, the lack of insight about the mechanisms producing single-mode behavior has prevented a complete description of single-mode lasers by any theoretical model.

7. M. Corti and V. Digiorgio, Phys. Rev. Lett. 36, 1173 (1976).

IV. OUTSTANDING FUNDAMENTAL PROBLEM

The fundamental interaction which reduces the complexity of the laser spectrum with increase in drive is not established, and its nature is the central problem in the theory of injection lasers. Several approaches to the solution of the problem present themselves, and the preferred one depends on the point of view about laser dynamics.

A. LINEAR PERTURBATION THEORY AS A GUIDE

On this point of view, single-mode lasers should be the general rule. The problem here is to explain why real lasers are multimode at threshold and why the gain increases with current. Solutions to the rate equation when several modes are oscillating are needed. The successes of this approach have been meager, in spite of its popularity, and it has given little insight or guidance to laser development or study.

B. P* THEORY

This is a multimode theory and its results apply to real lasers. Many effects disclosed by the formalism were later observed, and a simple modeling of the dielectric waveguide yields a good description of most of the dominant features of existing lasers. The one repeated failure of the modeling is the description of the dependence of power on wavelength, which always has a much steeper maximum than predicted.

If the fundamental nonlinear rate equation is valid, the failure of the model lies in the relation between overdrive parameter X and the measured value of the junction voltage, that is the voltage dependence of the function

$$X(V) \equiv (g/g_{th}) - 1.$$

Our model assumed that the loss coefficients of the modes (i.e., g_{th}) were fixed properties of the laser independent of operating conditions and time, and that the voltage dependence of g was given by the band calculation of Stern. Several effects can be suggested which might modify the model and describe the observed spectra.

(1). The gain spectrum $g(\lambda)$ has a very sharp maximum, superimposed on the band spectrum given by Stern, which is sufficiently narrow to excite only one spectral line. There are two difficulties with this: no such structure has been noted in the stimulated emission just below threshold; and a physical cause of such a structure is lacking.

(2). The loss spectrum (the modal dependence of g_{th}) is modified by the operation. A shift in the occupancy of localized states in the recombination region or cavity could make the losses a function of operation and perhaps also a sharp function of wavelength. This effect could also depend on laser structure.

A modification of the waveguide with pump level or time could modify the loss spectrum. One source is the change in thermal profile, which has quite an effect on oxide-stripe lasers. The spatial wandering of the modes and the change in dielectric profile could make the loss coefficients (as well as the gain coefficients) depend on the operating conditions.

(3). An effect suggested by North [8] is a fundamental modification of the dielectric waveguide with mode power resulting from the P^* interaction itself. The effect arises from the dispersion associated with the wavelength dependence of the gain function. Because of the P^* interaction, the actual gain in the lasing state becomes a sharp function of wavelength with deep dips at each lasing mode. These dips produce an appreciable modification of the waveguide of any specific mode by the power in adjacent modes, and tend, in principle, to single-mode behavior at higher powers.

The solution of this central problem of injection lasers, the tendency to single mode at high output, is sufficiently important to warrant a better empirical description of the properties of single-mode lasers. The experimental studies would be guided by the theoretical leanings of those involved in the work.

8. D. O. North, private communication.

V. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT

The following RCA Laboratories personnel were supported in part by the present contract:

H. Kressel, Project Supervisor;

H. S. Sommers, Jr. (partial), Project Scientist;

D. Botez (partial), Member of Technical Staff.

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7. M. Corti and V. Digiorgio, Phys. Rev. Lett. 36, 1173 (1976).
8. D. O. North, private communication.

APPENDICES

LIST AND ABSTRACTS OF ALL PUBLICATIONS UNDER THE CONTRACT

APPENDIX A. EXPERIMENTAL AND THEORETICAL STUDY OF THE SPATIAL VARIATION OF JUNCTION VOLTAGE AND CURRENT DISTRIBUTION IN NARROW-STRIPE INJECTION LASERS.

APPENDIX B. ASYMMETRIC MODES IN OXIDE-STRIPE HETEROJUNCTION LASERS.

APPENDIX C. ALGORITHM FOR MEASURING THE INTERNAL QUANTUM EFFICIENCY OF INDIVIDUAL INJECTION LASERS.

APPENDIX D. BEAMWIDTH APPROXIMATIONS FOR THE FUNDAMENTAL MODE IN SYMMETRIC DOUBLE-HETEROJUNCTION LASERS.

APPENDIX E. NEAR- AND FAR-FIELD APPROXIMATIONS FOR THE FUNDAMENTAL MODE IN SYMMETRIC WAVEGUIDE DH LASERS.

APPENDIX F. CURRENT DEPENDENCE OF SPONTANEOUS EMISSION AND OF JUNCTION RESISTANCE AS A TEST OF THE INTERNAL DYNAMICS OF INJECTION LASERS.

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APPENDIX H. EXPERIMENTAL PROPERTIES OF INJECTION LASERS: VIII. NARROW-STRIPE LASERS WITH INDUCED WAVEGUIDE.

APPENDIX I. A COMPREHENSIVE MODEL OF THE INJECTION LASER: FORMULATION AND TEST OF THE CURRENT DEPENDENCE OF SPONTANEOUS AND COHERENT EMISSION.

APPENDIX J. EXPERIMENTAL PROPERTIES OF INJECTION LASERS: IX. MODE POWERING IN LASERS WITH SIMPLE SPECTRA. (In preparation.)

APPENDIX A

EXPERIMENTAL AND THEORETICAL STUDY OF THE SPATIAL VARIATION OF JUNCTION VOLTAGE AND CURRENT DISTRIBUTION IN NARROW-STRIPE INJECTION LASERS, BY H. S. SOMMERS, JR. AND D. O. NORTH, J. APPL. PHYS. 48, 4460-4467 (1977)

ABSTRACT

The spatial variation of the junction voltage and current distribution are deduced from measured profiles of the intensity of high-frequency light across the emitting facet of stripe lasers. The dependence of voltage on current follows closely the current dependence deduced from study of the external beam. Below threshold, the shape of the voltage profile is found to be practically independent of current. The change at threshold in the differential conductance of the junction has only a minor effect on the profile, although its effect is observable over the entire front of the coherent waves. However, there is no apparent modification of the profile connected with the structure of the coherent illumination of the facet. A new theory is developed of the current spreading in a layered structure which successfully describes the features of the measured distributions. Using only material parameters of the layers of the laser, it predicts to good approximation the observed current spreading. The modifications to the voltage profile on transit of threshold are treated as perturbations, which introduce a new parameter related to an effective total impedance of the junction. A single-parameter fit of the theory at each power gives a good account of the corresponding profile. In principle, the parameter can be calculated, but the necessary model of the lasing modes is lacking.

APPENDIX B

ASYMMETRIC MODES IN OXIDE-STRIPE HETEROJUNCTION LASERS, BY J. K. BUTLER AND H. S. SOMMERS, JR., IEEE J. QUANTUM ELECTRONICS QE-14, 413-417 (1978)

ABSTRACT

The region between the pair of heterojunctions of an oxide-stripe laser is modeled by a step profile in the lateral distribution (parallel to the heterojunctions) of the gain and of the refractive index, in an attempt to gain insight about the interpretation of the asymmetric radiation patterns frequently observed. A region W_a concentric with the stripe contact is subdivided into three sections. The gain and index are uniform in each of the sections. The step heights for the gain distribution and for the index distribution are given complementary symmetry with the gain maximum superimposed on the index minimum. Asymmetry is introduced by lateral shift of the extrema at fixed W_a. With values of gain, index step, and W_a that seem reasonable for the laser studied, the near and far fields reproduce the measured profiles of a representative 10-μm stripe laser. The offset of the spontaneous profile is about 3 μm from the center of the stripe, and the beam has a single lobe for all low-order modes with offset of order 5° from the facet normal. Because of the near cancellation of gain-guiding by index antiguiding that is required to give the observed asymmetries, the propagation constant becomes very sensitive to injection level; this may explain the observed nonmonotonic change of modal power and the very rapid shift of modal wavelength with current.

APPENDIX C

ALGORITHM FOR MEASURING THE INTERNAL QUANTUM EFFICIENCY OF INDIVIDUAL INJECTION LASERS, BY H. S. SOMMERS, JR., APPL. PHYS. LETT. 32, 547-549 (1978)

ABSTRACT

A new algorithm permits determination of the internal quantum efficiency η_i of individual lasers. Above threshold, the current is partitioned into a "coherent" component driving the lasing modes and the "noncoherent" remainder. Below threshold the current is known to grow as $\exp(qV/n_o KT)$; the algorithm proposes that extrapolation of this equation into the lasing region measures the noncoherent remainder, enabling deduction of the coherent component and of its current derivative η_i. Measurements on 5 (AlGa)As double-heterojunction lasers cut from one wafer demonstrate the power of the new method. Comparison with band calculations of Stern shows that n_o originates in carrier degeneracy.

APPENDIX D

BEAMWIDTH APPROXIMATIONS FOR THE FUNDAMENTAL MODE IN SYMMETRIC DOUBLE-HETEROJUNCTION LASERS, BY D. BOTEZ AND M. E. ETTENBERG, IEEE J. QUANTUM ELECTRONICS QE-14, 827-831 (1978)

ABSTRACT

The beamwidth for the fundamental TE_0 mode in symmetric DH lasers is approximated within 4 percent by analytical formulas covering wide ranges of cavity thickness and refractive index steps. By using a Gaussian approximation for near-field distributions, and numerically calculated beamwidth curves, we find a Gaussian beam-like expression for the beamwidth, over the range $1.5 < D < 6$, where D is the normalized guide thickness. In the nonGaussian region $0 < D < 1.5$, the beamwidth is estimated by using a corrected Dumke-like asymptotic approximation.

APPENDIX E

NEAR- AND FAR-FIELD APPROXIMATIONS FOR THE FUNDAMENTAL MODE IN SYMMETRIC WAVEGUIDE DH LASERS, BY DAN BOTEZ, RCA REV. 39, 577-603 (1978)

ABSTRACT

Analytical approximations of near- and far-field parameters characterizing the TE_o mode propagation in symmetric double-heterojunction waveguides are described. The use of trigonometric function approximations permits estimating the mode phase shift at the dielectric interface within a few percent over the whole range of D (normalized waveguide thickness); as a result, approximations within 1% are obtained for: the field intensity in the waveguide, the effective waveguide thickness, and the effective waveguide index. Gaussian approximations are used for estimating near- and far-field intensity profiles over intermediate D ranges ($1.8 < D < 6$ and $1.5 < D < 5$, respectively) and for $\Delta n/n \leq 10\%$. The laser beamwidth in the transverse direction θ is obtained with 4% maximum error by use of a Gaussian approximation for $1.5 < D < 5$, and a corrected asymptotic formula for $0 < D < 1.5$. An accurate analytic approximation is also obtained for the laser transverse far-field pattern in the non-Gaussian region $0 < D < 1.5$, $\theta < 40°$.

APPENDIX F

CURRENT DEPENDENCE OF SPONTANEOUS EMISSION AND OF JUNCTION RESISTANCE AS A TEST OF THE INTERNAL DYNAMICS OF INJECTION LASERS, BY H. S. SOMMERS, JR., APPL. PHYS. LETT. 34, 422-444 (1979)

ABSTRACT

An expression is derived for the current dependence of spontaneous emission in the lasing state. It shows that the slope of the emission above threshold is controlled by a product of two terms, only one of which is affected by the dynamics of lasing. Since the other depends on subthreshold properties, the slope of the spontaneous characteristic is not a definitive test of laser models. While a rise in spontaneous emission above threshold is inconsistent with the linear rate equations describing the stimulated recombination, a strong saturation does not support them. As an example, comparison of the properties of the laser of Paoli and Barnes which exhibited a strong saturation with data on other stripe units with various degrees of saturation shows that the unusually strong saturation they find is caused by an unusally low product of threshold current and external efficiency, not by a different form of the rate equation. As an aside it is shown that the slope ratio also measures the ratio of junction resistances above and below threshold.

APPENDIX G

EXPERIMENTAL PROPERTIES OF INJECTION LASERS: VII. NARROW-STRIPE LASERS WITH RIGID WAVEGUIDE, BY H. S. SOMMERS, JR., J. APPL. PHYS. 50, 6621-6629 (1979)

ABSTRACT

The properties of a type of (AlGa)As double-heterojunction laser with buried cavity are studied as a function of current and of delay after the start of a 10-μs-square current pulse. It is found that the waveguide walls are rigid, for the mode shapes, mode dispersion, threshold, efficiency, and power-current characteristic are invariant of current and delay. The spectra are also independent of delay except for a wavelength shift from the change of temperature. The modes are tightly confined with a half-width of 2 μm of the fundamental mode at the facet. The two lowest spatial modes dominate the emission, which is almost completely contained in one spectral doublet. The power in each member of the doublet (single-mode power) is linear in junction voltage from less than 100 μW to the full output of 3 mW, with slope giving a critical power $P^* \approx 10$ mW as in wide lasers with rigid guides. The strong doublet is transferred to successively longer wavelength modes as the current or delay is increased. The transfer suggests that a narrow gain profile is being swept past the cavity modes by a rise in temperature.

APPENDIX H

EXPERIMENTAL PROPERTIES OF INJECTION LASERS: VIII. NARROW-STRIPE LASERS WITH INDUCED WAVEGUIDE, BY H. S. SOMMERS, JR., J. APPL. PHYS. 50, 6630-6642 (1979)

ABSTRACT

The properties of a type of cw AlGaAs injection laser whose waveguide is produced or modified by the conditions of operation are studied as a function of current and of delay after the start of a 10-μs square current pulse. They are illustrated by data on a representative unit from a popular structure, the oxide stripe laser, operating in the fundamental spatial mode and with linear power-current characteristic. At the start of the pulse the laser behaves like an oscillator with rigid cavity walls, with mode profiles invariant of current, mode powers linear in junction voltage, and smooth envelope of the spectrum. With delay, all these properties are lost; the beam changes its shape and direction, the shape and position of the coherent near field are changed, and the spectral envelope changes erratically. Since the voltage profile across the facet retains its shape and symmetry and is invariant of delay, the effects are not associated with modifications of the profile of gain or free carriers. They seem to be due to development of a temperature profile beneath the stripe contact. Comparison at fixed current between the changes with delay of the profiles of the modes and the change in propagation constant strengthens the interpretation. Analysis of this laser shows that a 15% increase in free-carrier density is inconsequential to the observed mode confinement, and that spatial hole burning has no role in the modification of its waveguide.

APPENDIX I

A COMPREHENSIVE MODEL OF THE INJECTION LASER: FORMULATION AND TEST OF THE CURRENT DEPENDENCE OF SPONTANEOUS AND COHERENT EMISSION, BY H. S. SOMMERS, JR., J. APPL. PHYS. 1932-1945 (1980).

ABSTRACT

Extrapolation of the conventional diode equation into the oscillating region gives formal expressions for the internal and external efficiencies in terms of waveguide parameters, threshold current, and the voltage derivative of laser power. The latter, which depends on band and laser theory, is examined for two models. Linear perturbation theory gives qualitative conclusions which are of little utility for actual devices. Combination of diode analysis with the band theory of Stern and the P* theory of North gives a comprehensive theory of the current dependence of the static properties of the laser. The assumptions of the extrapolation are discussed, and experimental examples are presented to illustrate the utility of the new diode analysis. The comprehensive theory is used to interpret various known properties of devices such as linearity of power with current, change of internal efficiency with waveguide thickness, change of junction resistance at threshold, and several scaling laws. The types of experiments to test the theory are discussed and, in particular, the properties peculiar to the P* interaction. Many studies of the latter have shown its rather general applicability, but its utility for "pure mode" lasers with narrow spectra has not yet been thoroughly studied.

APPENDIX J

EXPERIMENTAL PROPERTIES OF INJECTION LASERS: IX. MODE POWERING IN LASERS WITH SIMPLE SPECTRA, BY H. S. SOMMERS, JR., (UNDER PREPARATION FOR PUBLICATION IN J. APPL. PHYS.)

(No abstract)